Shear viscosity measurements at the vortex melting transition in confined geometry in optimally doped Bi2Sr2CaCu2O8

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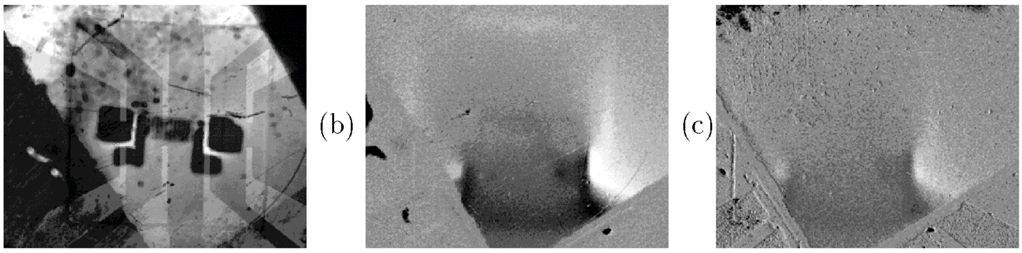
Abstract.

In order to probe the vortex shear viscosity in the vortex liquid phase, we have introduced two types of vortex-confining structures in optimally doped $Bi_2Sr_2CaCu_2O_8$ single crystals. First, walls of strong vortex pinning separated by weakly pinning channels are fashioned by heavy ion irradiation through 25 μm-thick Ni masks. Second, a low density of homogeneously distributed amorphous columnar defects is known to impose a polycrystalline structure to the vortex lattice. Resistivity measurements show that the inclusion of confining structures impede vortex flow in the liquid. The resistivity is remarkably well described by the Halperin-Nelson theory for the viscosity due to free two-dimensional vortex lattice dislocations.

1. Introduction

The nature of the vortex liquid in clean and disordered high temperature superconductors (HTSC), and the role of vortex lattice dislocations and grain boundaries in depinning and transport properties of superconductors in a magnetic field, are among the open questions still debated within the field of vortex physics. The vortex ensemble in single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$ is known to melt via a first order phase transition (FOT) from a vortex solid phase, with long range order of the phase of the superconducting order parameter, to a vortex liquid without long-range order [1]. Measurements on heavy-ion irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals containing 2.5 μm wide unirradiated (weakly pinning) channels suggest that the vortex lattice shear modulus vanishes at the FOT temperature T_m [2]. However, the channels of Ref. [2] extended to the edge of the crystals, and the onset of vortex flow could be equally well explained by the demise of a surface barrier at the FOT [3]. Magnetic decoration [4] and Josephson Plasma Resonance data [5] taken near the FOT in low magnetic fields suggests that vortex lattice transverse order is irrelevant for the FOT mechanism, and that it is vortex line integrity along the field direction that is lost due to vanishing Josephson coupling. Further investigations



(a) (b) (c)

Figure 1. (a) Superposition of a photograph of the electrical contacts deposited on the surface of crystal # 1, and an MO image showing the position of the channel structure and irradiated contact pads. The current, perpendicular to the channels, is injected from the bottom outside pair, voltage is measured for the bottom inside pair. (b) Differential Magneto-optical image obtained by subtracting images taken with transport currents of (+25mA, -25mA) running through crystal # 1 ($T = 78$ K, $H = 0$). (c) As (b), in $H = 100$ Oe.

have shown that the addition of a small density of amorphous columnar defects transforms the vortex lattice to a polycrystal, but does not affect the FOT [6]. The transition to a homogeneous vortex liquid was suggested to take place via a two-step process, in which the melting of unpinned vortices within the polycrystal grains is followed by the depinning (at T_{dl}) of vortices located on the "matrix", or grain boundaries, formed by the columnar tracks [7].

The measurement of the vortex shear viscosity η and friction coefficient γ has long been suggested as a valuable tool to discriminate between different scenarios describing the onset of vortex mobility [8]. Measurements of the shear viscosity on channel structures prepared in (two-dimensional, 2D) superconducting thin films have confirmed the Halperin-Nelson theory [9] for dislocated mediated melting [10]. The resistivity ρ in the vortex liquid is then given by

$$\rho \propto C_2 \exp\left[-2C_1\left(\frac{T_m}{T-T_m}\right)^{0.37}\right], \tag{1}$$

with C_1 and $C_2 \approx 1$ constants.

Here, we present the first report on a similar experiment on (three–dimensional) layered $Bi_2Sr_2CaCu_2O_{8+\delta}$. We find that the inclusion of a small density of columnar defects reduces the vortex mobility above the FOT in much the same way as the channel structures of Ref. [10] do. Moreover, the resistivity in the relevant temperature regime accurately follows Eq. (1), suggesting that transport is due to the motion of 2D vortex segments and that the FOT indeed corresponds to the loss of vortex line integrity.

2. Experimental Details

Optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals were obtained from a batch grown using the travelling-solvent floating zone technique under 200 mBar O_2 partial pressure, by annealing at 800°C for six hours [11]. All crystals were checked for the absence of macroscopic defects by the magneto-optical imaging (MOI) technique. An array of 12 channels, separated by walls of strong flux pinning was prepared in two of the crystals by irradiation with 1×10^{11} cm^{-2} 1 GeV Pb^{56+} ions through a 25 μm-thick Ni mask. In order to exclude the effects of a surface barrier, the channel structure as well as irradiated contact pads were located in the central areas of the crystals, remote from the edges [3]. One of the crystals (# 2, $T_c = 88.5$K) and a third crystal without channel structure (# 3, $T_c = 87$ K) were subsequently homogeneously irradiated with a fluence of 5×10^7 cm^{-2} 1 GeV Pb ions. This corresponds to a dose-equivalent matching field $B_\phi = 10$ G.

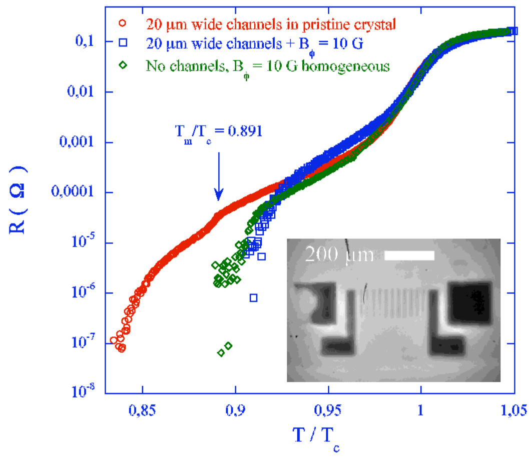


Figure 2. Resistance vs. temperature in $H = 166$ Oe, for the three $Bi_2Sr_2CaCu_2O_8$ crystals. The inset shows a magneto-optical image of the central part of crystal # 2, taken at $T = 35$ K and an applied field $H = 456$ Oe. The bright areas correspond to those parts of the crystal that are permeated by vortices, the dark zones are the irradiated areas that screen the field.

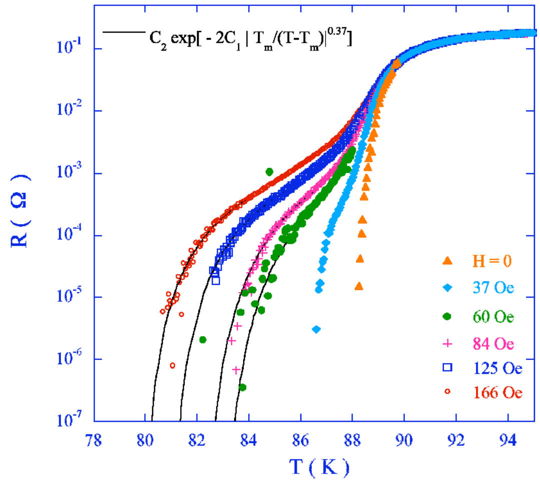


Figure 3. Resistivity vs. temperature for crystal # 2 (20 μm-wide channels in crystal with $B_\phi = 10$ G), for different values of the applied magnetic field. Drawn lines represent fits to Eq. (1).

The channel structures were characterized using MOI. The inset in Fig. 2 shows an image of the central area of crystal # 2. After zero-field-cooling, the irradiated areas screen out an applied magnetic field H, while the rest of the (weakly-pinning) crystal is permeated by vortices.

The crystals were subsequently glued on a 200 μm–thick sapphire substrate, and Au contact pads were evaporated [Fig. 1(a)]. The current flow through the channel structure was verified using Differential MOI with modulated transport current, similar to Ref. [7]. Fig. 2(b,c) show that in zero applied field, the transport current runs both through the channel structure and along the crystal boundary; in an applied field of 100 Oe, the crystal boundary is invisible, current flowing only through the channel structure. After the MOI characterization, four-probe dc transport measurements were performed with a current of 8 mA. We checked that no nonlinearities or heating affect the present data.

3. Results

Fig. 2 shows the temperature dependence of the resistivity for the three crystals in $H = 93$ Oe. In spite of the inclusion of the strongly pinning contact pads and channel walls, the resistivity of crystal # 1 shows the same behaviour as that found in Ref. [3]. Notably, the signature of the vortex FOT transition is clearly observable at $T/T_c = 0.891$. This result shows that no defects were introduced in the weakly pinning channels.

The resistivity of crystal # 2 (20 μm wide channels plus 5×10^7 cm^{-2} columnar tracks) follows nearly the same temperature dependence as that of crystal # 1, but starts to fall below it as T_m is approached from above, at a temperature identified as T_{dl} in Ref. [7]. The behaviour is much the same as that of the homogeneously irradiated crystal # 3, in which the resistivity falls off at a slightly lower temperature. The suppression of the resistivity by the confinement of the vortex liquid in the artificial pores created by the 5×10^7 cm^{-2} homogeneous irradiation strongly resembles that obtained in Tesla fields in α–Nb_3Ge [10].

In the temperature range between T_m and "T_{dl}", the resistivity of samples #2,3 can be very well described using Eq. (1), using a prefactor C_2 of the order of the normal state resistivity, $C_1 \approx 1.1$, and the *experimental* T_m. The resistivity can also be described using the Bose glass form $\rho \sim |T - T_G|^s$ [8], with $s \approx 2.5$. However, in contradiction to theoretical expectations [12], s is larger for the homogeneously irradiated crystal. Also, the obtained T_G-values bear no obvious correspondence to experiment.

4. Discussion

Two of the above crystals contain strongly pinning areas with 1×10^{11} cm^{-2} columnar defects ($B_\phi = 2$ T). Similar strongly pinning areas with much lower column densities were suggested to strongly decrease the resistivity due to the localisation effect of the columnar defects [7]. No such effect can be seen here. However, the decrease of $R(T)$ due to the addition of a small columnar defect density (5×10^7 cm^{-2}) does produce the effect reported in Ref. [7], except from the lack of any sharp feature previously reported at "T_{dl}". We surmise that the decrease of the resistivity for $T_m < T < T_{dl}$ is therefore not due to the (de)pinning of vortices from the columnar defect matrix, but to the inhomogeneous shear of unpinned 2D pancake vortices through the pores defined by the columnar defect ensemble. This results in a vortex diffusion coefficient that has the form (1). The fact that this decribes a 2D vortex system confirms that flux transport in the vortex liquid takes place through the motion of individual pancake vortices, and not of correlated vortex lines, and that the FOT must therefore correspond to a loss of vortex line integrity. As for the 20 μm wide channel structures, they seem to bear little effect on the resistivity, only a small change being observed between the behaviour of samples # 2 and # 3.

Finally, the temperature dependence (1), or the Bose glass form $\rho \sim |T - T_G|^s$ that mimics it, is observed even as a weak first order phase transition of the vortex ensemble [6] is approached from above. Thus, many previous experiments reporting on Bose-glass behaviour in heavy-ion irradiated HTSC crystals for $B > B_\phi$ may in fact have been probing vortex shear, and cannot be seen as definitive when it comes to a change in order of the vortex solid-to-liquid transition.

5. Conclusion

Electrical transport measurements on optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals containing channel strucxtures defined by heavy ion-irradiation performed through Ni masks show that the resistivity in the vortex liquid shows the Halperin-Nelson behaviour for the diffusion of free 2D vortex lattice dislocations. We identify the moving object with free 2D pancake vortices moving from vortex line to vortex line.

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